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(54) **Optical member made of high-purity and transparent synthetic silica glass and method for production thereof and blank thereof**

Optisches Bauteil aus hochreinem und transparentem, synthetischem Quarzglas und Verfahren zu seiner Herstellung und sein Rohling

Membre optique en silice synthétique de haute pureté et transparente et méthode de fabrication et ébauche de celui-ci

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## Description

## BACKGROUND OF THE INVENTION

## 5 [Field of the Invention]

The present invention relates to an optical member made of synthetic silica glass of high-purity and transparency, and a method for manufacture a blank thereof or the optical member. The invention relates more especially to optical members assembled in various apparatuses employing such high-power laser beams as an excimer laser, or optical members assembled in apparatuses used in a radiation environment where they are exposed to a gamma ray, an X-ray or cosmic rays.

## [Description of the Prior Art]

15 In recent years it is noted that the high-power lasers such as the excimer laser, etc. are applicable to a lithographic technique for producing large scale integrated circuits (LSIs), a technique applying photo-chemistry, a processing technique for cutting and grinding, or laser nuclear fusion.

Attempts have been made to apply the silica glass optical members such as lenses, prism, mirrors, optical fibers not only for communication but mainly for light or energy transmissions, or other optics, to transmit, to refract, to reflect, 20 to absorb or to interfere the high-power laser beams.

Attempts have also been tried to apply the silica glass optical members such as lenses, prism, mirrors, fibers and so forth assembled in an optical apparatus for spacecraft, or an optical apparatus for nuclear reactor periphery operating in a radiation environment where they are exposed to gamma rays, X-rays or cosmic rays.

In the event, however, when the various optics made of silica glass are irradiated with visible light having wave lengths ranging from about 700 to 600 nm, ultraviolet light having wave lengths ranging from about 360 to 160 nm, or ionized radiation beams, the optics are apt to suffer structural damages.

An absorption band of wave length about 630 nm exhibits the defect what is called as a non-bridging oxygen hole center (NBOHC). An absorption band of wave length about 215 nm is the so called E' center. And there is another absorption band of wave length about 260 nm. Those absorption bands are generated upon irradiation of high-power laser beams in a long period, resulting in reducing the optical transmission for the visible light having wave lengths ranging about from 750 to 500 nm, and for the ultraviolet light having wave lengths ranging from about 360 to 160 nm to deteriorate the optical properties of the material.

It is, therefore, very difficult to improve the durability of silica glass against the high-power laser irradiation of which beams have the wave lengths described above, because the glass suffers the structural damages.

35 Further, it is confirmed that among the various types of lasers, the KrF excimer laser and the ArF excimer laser are the most powerful to subject the silica glass to be optically damaged.

The present inventors have first tried to produce an optical member with a fair measure of success from a standard synthetic silica glass of high-purity and high-homogeneity.

The study has been progressed by the inventors to develop the technique filed by the inventors as Japanese Pat, 40 Appln. 1-145226, which is called as a prior application technique hereinafter, for doping with hydrogen in the synthetic silica glass described above as a basic material to suppress drastically the optical damage on the irradiation of ultraviolet having a wave length less than about 250 nm.

In the doping method of the prior application technique, however, hydrogen is more doped in the surface region of the glass in contact with the dopant gas. It is rather difficult to dope homogeneously in the entire solid glass even in an atmosphere of elevated temperature. The difficulty tends to be amplified with the increase of the thickness of the glass to be doped. In this doping method, therefore, the laser damage prevention effect is limited to a certain maximum thickness.

Because the glass members for laser use should be high-purity and high-homogeneity synthetic glass, other starting can not be used as the starting materials. Since in the synthetic process is subjected within a short time in an elevated temperature of oxyhydrogen flame, the reaction process seemingly is not sufficient to reached to an equilibrium state to produce a stable structure. Therefore, the synthetic glass includes a glass structure of three member rings or four member rings which are not detected in a quartz. It is believed that the unstable structures may reflect to the decrease of durability against laser irradiation. It is confirmed that the silica glass having the higher scattering peaks of wave numbers of 495 and 606  $\text{cm}^{-1}$  with the laser Raman scattering spectrometry is inferior in the laser durability.

55 To obviate the issue by the inventors as described above, the structure has been reformed with hydrogen doping. The procedure was merely a relief remedy not solving the issue substantially, but instead including the limitation on feasible thickness for doping as stated previously.

Once the synthetic silica glass has suffered the light or irradiation damage, a chemical bond between silicon and oxygen of network structure generally is rendered to split, which rejoins with other structures thus increasing the density and the local absolute refractive index.

Even in the events when the refractive index is increased due to the breakage and recombination of the bonds between silicon and oxygen, with the presence of hydrogen molecules near the split bond, an OH group is formed by reaction with hydrogen molecules provided in the silica glass, wherein the most of the split bonds are remedied to suppress the increase of refractive index. There still remains another issue to be solved when the silica glass is exposed to the high-power laser beam for a long period.

That is, though the initial deterioration can be improved with the presence of hydrogen, a further irradiation with the high-power laser beam causes to exhaust the hydrogen within a short time, even if the hydrogen is included a concentration of more than  $5 \times 10^{16}$  molecules/cm<sup>3</sup>. No remedial effect can be expected with a hydrogen concentration of less than  $1 \times 10^{16}$  molecules/cm<sup>3</sup>.

In the prior technique as described above, the technique for doping the silica glass with hydrogen is disclosed for the treatment in atmospheric or high pressure gas at the elevated temperature from 200 to 1200°C. A similar technique for doping with hydrogen is also disclosed in Japanese Laid Open Pat. Appln. No. 1-201664, showing a technique possible for doping at atmospheric pressure ambient at an elevated temperature from 800 to 1,000°C.

These techniques handling the hydrogen at an elevated temperature involve the explosion hazard for which safety cares must be taken.

## SUMMARY OF THE INVENTION

### [Objects]

In considering the issues of the prior techniques above, it is an object of the present invention to provide an optical member durable against high-power laser irradiation for a long period assuring the optical durability under laser irradiation, high-power light exposure, or ionizing irradiation for a long time. Such a feature mentioned above is called as 'durability against laser irradiation' hereinafter.

Another object of the present invention is to provide a lump of optical glass having the durability against laser irradiation, in which, even though a lump of synthetic glass is used as a starting material, the synthetic glass is then subjected to a heat treatment as needed with an intention to make the structure densified and stabilized.

Still another object of the present invention is to provide a lump of silica glass in a large size having the durability against laser irradiation. And the silica glass is grounded to very thick prisms or lenses without limitation to a certain thickness.

Yet still another object of the present invention is to provide a method for produce an optical member made of silica glass including hydrogen molecules in the safest way without hydrogen explosion hazard.

### [Constitution of the Invention]

#### [A. Synthetic Silica Glass]

The present invention is based on a prerequisite to use synthetic glass, more preferably, to use synthetic glass of high-transparency. The basic material to acquire the durability against laser irradiation, as described previously, should be high-purity, high-homogeneity, and of high-transparency. No other material than the synthetic silica glass can satisfy the conditions. The synthetic process time, however, is so short in an elevated temperature, that silica glass network structure can not relaxed to a stable structure.

It has been confirmed by the inventors, in the case when the synthetic glass has not reached to the equilibrium state, that the unstable structure contains 3-member rings, or 4-member rings (F.L. Galeener, J. Non-Crys. Sol., 49 (1982)). Further study by the inventors has revealed the facts that the 3-member rings and 4-member rings are rendered to reduce, while 6-member rings of the stable structure increase, if the silica glass is subjected to a heat treatment under a pressurized atmosphere.

It has been found by the inventors that the durability against laser irradiation is sufficiently secured even with the irradiation of the high-power laser beam when the absolute refractive index,  $n_d$ , at a wave length of 589 nm is kept 1.460 or higher. This constitutes the first feature of the present invention.

With the first feature, since the structure of the glass is stabilized with achieving the intention to make it densified, the bond breakage between silicon and oxygen is suppressed, wherein the intention can be realized to suppress the decreasing of optical transmission and the local increasing of the absolute refractive index.

Additionally, the structure of 3-member rings and 4-member rings can be easily measured with a laser Raman scattering spectrometry referring the scattering peak ( $800 \text{ cm}^{-1}$ ) for the basic vibration between silicon and oxygen by Eqs. 1 and 2 as follow:

$$R1 = I_1 / I_0 \quad (495 \text{ cm}^{-1}) / I_0 \quad (800 \text{ cm}^{-1}) \quad \text{Equ. 1,}$$

$$R2 = I_2 / I_0 \quad (606 \text{ cm}^{-1}) / I_0 \quad (800 \text{ cm}^{-1}) \quad \text{Equ. 2,}$$

5 where,

$I_1$ : intensity of scattering peak at  $495 \text{ cm}^{-1}$ ,  
 $I_2$ : intensity of scattering peak at  $606 \text{ cm}^{-1}$ , and  
 $I_0$ : intensity of scattering peak at  $800 \text{ cm}^{-1}$ .

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The intensity ratios, for example, for a standard synthetic silica glass, of which absolute refractive index  $n_d$  is 1.458, are  $R1 > 0.55$  and  $R2 > 0.17$ . On the other hand, the intensity ratios for the synthetic glass having the absolute refractive index  $n_d$  higher than 1.460 can be reduced at least  $R1 < 0.55$  and  $R2 < 0.17$ , and more preferably,  $R1 < 0.48$  and  $R2 < 0.15$ .

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Furthermore, the probability of bond breakage between silicon and oxygen atoms is strongly influenced by the materials stoichiometry. It has been found by the inventors that a surplus of oxygen atoms, as a result of a high oxygen flow rate during material deposition, results in the creation of non-bridging oxygen hole centers (NBOH). These NBOH-centers show a strong UV-light induced broad absorption centered at 265 nm wavelength, thus badly influencing the light transmission below 300 nm. Furthermore, the creation rate of the 215 absorption band under UV-light exposure is increased.

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On the other hand, as found by the inventors, a small deficiency of oxygen atoms in the material, as a result of a low oxygen flow rate during material deposition, completely avoids the creation of the 265 nm NBOH-absorption band and strongly depresses the creation rate of the 215 nm absorption.

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By avoiding an oxygen surplus in the material, wherein the materials stoichiometry is set to  $\text{SiO}_{2+x}$  with  $x$  in the range of +0.0001 to -0.001, the structure of the glass is stabilized and the decreasing of the optical transmission is further suppressed.

Even with the first feature mentioned above, it is impossible to completely eliminate the unstable structures. Though the breakage of bonds between silicon and oxygen atoms is suppressed, it is impossible to eliminate it completely.

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Then, the present invention provides as the second feature to dissolve in the glass structure hydrogen molecules of concentration about more than  $1 \times 10^{17}$  molecules/cm<sup>3</sup> for the optical member applied especially for the high-power ultraviolet laser.

With the second feature, even though the bond breakage between silicon and oxygen been occurred, the reaction with hydrogen molecules prevents the formation of color centers, suppressing the decrease of optical transmission. Even though the bond breakage between the elements does occur, the formation of OH group prevents the increase of refractive index.

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Since the present invention has established the absolute refractive index,  $n_d$ , to be higher than 1.460, the bond breakage is rendered to have little further effect. Thus, the consumption of hydrogen molecules results in prolonging drastically the durability against laser irradiation.

Some of rare gases may be included in the optical members together with hydrogen. The rare gas doping improves the glass network structure for more stable structure to modify preferably the optical features.

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Besides the increasing refractive index and the stabilized glass structure containing hydrogen molecules therein, the other optical properties must be considered.

The wide ranges of the refractive index-inhomogeneity,  $\delta n$ , are not suitable for lenses or prisms application.

In the preferred embodiment of the present invention, the refractive index-inhomogeneity,  $\delta n$ , along the axis of incident light beam should be less than  $5 \times 10^{-6}$ , more preferably, less than  $2 \times 10^{-6}$  inclusively.

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It has been shown by traditional techniques to improve the durability against laser irradiation that the metallic elements in the silica glass should be reduced. The presence of metallic elements decreases sharply the optical transmission within the range of ultra violet wave lengths, or more practically, decreases steeply the transmission at the wave length about 200 nm, which is not suitable for optical members.

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The present invention, therefore, has established that the total content of Li, Na, and K is 300 mass ppb or less, the total content of Mg and Ca is 200 mass ppb or less, the total content of Ti, Cr, Fe, Ni and Cu is 500 mass ppb or less, and more preferably, the content of each elements of Na, K, Li, Mg, Ca, Ti, Cr, Fe, Ni and Cu is less than 100 mass ppb.

Contrarily to the above, the presence of OH group is preferable, which produces the desirable effects of improved durability against irradiation of ultraviolet laser beam for an extended period.

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The OH group is one of the network terminators. The presence of an appropriate amount of the network terminators relieves strains of interatomic distance and distorted angles between the atoms in the structure, whereby the structure becomes relaxed. It is further believed that the hydrogen of OH group acts to prevent the generation of the absorption bands such as the  $E'$  center.

In the present invention, therefore, the content of OH groups is established to be more than 180 mass ppm for the synthetic silica glass optical member applicable for the high-power ultraviolet laser having a wave length about 250 nm or less.

Adding to the above, chlorine also acts as similar to OH groups as the network terminator. The bond energy, however, between silicon and chlorine is much weaker than that of silicon and OH group. The presence of chlorine, therefore, is unfavorable for the durability against laser irradiation.

In the present invention, therefore, it is established that the content of chlorine in the optical member should be less than 500 mass ppm, or more preferably, the content of chlorine should be 200 mass ppm, or less.

The optical member is applicable not only for an excimer laser beam, YAG harmonics laser beam and other apparatuses adopting high-power ultraviolet laser beams, but also for lenses, prisms, windows, mirrors and light energy carriers or blanks thereof in an environment exposed by gamma rays, X-rays, cosmic rays or other radiation. It is preferably recommended to adopt the optical member formed of the transparent synthetic silica glass having the absolute refractive index  $n_d$  of 1.460 or more, containing hydrogen molecules of concentration about more than  $5 \times 10^{16}$  molecules/cm<sup>3</sup> to an optical apparatus of which light source is either one of a YAG laser (1,064 nm), a He-Ne laser (633 nm), an Ar laser (from 350 to 515 nm), a KrF laser (248 nm) or an ArF excimer laser (193 nm).

Among the above applications, the apparatus assembled with the optical member of the present invention, of which light source is the high-power excimer laser having the energy density of more than about 10 mJ/cm<sup>2</sup> per pulse, is assured its durability against laser irradiation enough to practical use, comparing to the traditional one which is apt to deteriorate its optical characteristics with traditional optical members for an extended period.

#### [B. Generation of Hydrogen Molecules]

In the prior art, the dissolution of hydrogen in silica glass is performed with diffusion doping. The hydrogen diffusion doping method, as described previously, forms high-concentration of hydrogen at the surface region directly contacting with ambient hydrogen gas. It becomes the more difficult to diffuse the gas uniformly into the internal region, when the thicker of glass is.

To achieve the object of the present invention, therefore, it requires a technique to include the hydrogen gas or molecules in the internal region. The heat treatment as described in the prior techniques in a high pressure hydrogen atmosphere at an elevated temperature still raises the safety problem against explosion.

In the present invention, a measure is thought to form hydrogen molecules from such hydrogen elements as water, OH group or proton (H<sup>+</sup>) included in the silica glass, without using hydrogen molecules in the ambient gas. To perform the measure above, the glass containing hydrogen elements such as water, OH group or proton (H<sup>+</sup>) should be used as a starting material.

Thus, as the third feature of the present invention, the starting material is the synthetic silica glass, or more preferably, the ingot of synthetic silica glass prepared by an oxyhydrogen flame hydrolysis method.

In several production methods of synthetic silica glass such as the direct oxyhydrogen flame hydrolysis method (direct method, in short) or a CVD soot remelting method (soot method, in short) the oxyhydrogen flame is used. The origin for hydrogen molecules such as proton (H<sup>+</sup>) are naturally included in the silica glass during the synthesis.

In the present invention, the starting material is a lump of transparent silica glass, because the present invention is aimed to large size of products circumventing the difficulties of doping hydrogen into thicker materials. The starting materials of powder or layer sheet type are not suitable for the optical member, since a succeeding fusing procedure in high-pressure atmosphere leaves sometime bubbles or granular structure in the glass resulting in to reduce the durability against laser irradiation.

As the fourth feature of the present invention, the inventors provide means for developing the origin of hydrogen elements to hydrogen molecules. The means comprises a step for heating the ingot of synthetic silica glass to remelt under a pressurized atmosphere of rare gases, and a step for keeping the atmosphere in a remelting state for a period as needed.

Though the reason why hydrogen molecules are generated in the process is not clear, it is possible to suppose that protons (H<sup>+</sup>), OH groups and water loose-jointed in the network structure of glass are disrupted or decomposed to generate hydrogen molecules under the pressurized atmosphere at the elevated temperature.

It is made possible to contain hydrogen molecules in the structure of glass under the atmosphere without hydrogen gas, if the atmosphere is satisfied with the two conditions described above. The ambient gas of atmosphere ought not be limited to the 100% rare gases. An atmosphere including a small amount of hydrogen or nitrogen, for example, works for the purpose.

The hydrogen molecules generated in glass may be diffused to outside of glass, if the atmosphere is subjected to reduce the pressure without interruption. Further, strains may be formed in glass which is not suitable for the optical member, if the atmosphere is subjected to cool rapidly to solidify the remelting glass succeeding to the step for reducing the pressure.

The present invention, therefore, adding to the two features described above, is characterized in a step to cool slowly the remelted silica glass at least to the strain point under the pressurized atmosphere.

Thus, it is possible to be free from residual strain in glass having the birefringence of 5 nm/cm or less, whereby the preferable optical member is provided.

#### [C. Method for Production]

A method for production of the optical member mentioned in the article A. will be described. The optical member contains hydrogen molecules with the concentration substantially evenly distributed through out the glass regardless to the thickness of the silica glass with the enhanced refractive index.

The present invention is based on a prerequisite to use synthetic glass, more preferably, to use synthetic glass of high-transparency as a starting material. The starting material to acquire the durability against laser irradiation, as described previously, should be high-purity, high-homogeneity, and high-transparency. No other material than the synthetic silica glass can satisfy the requirements.

The lump of glass is adopted as the starting material, instead of powdery or granular materials even made of synthetic silica glass, because the material is subjected to heat treatment for remelting under the pressurized atmosphere, and then to cool leaving bubbles or granular structure in the solidified glass resulting to reduces the durability against laser irradiation.

Thus, the fifth feature of the present invention lies in heating the ingot of high-purity high-transparency synthetic silica glass in a high-pressure atmosphere substantially consisting of inert gases, more precisely, heating in inert atmosphere at an elevated pressure at the temperature of 1,600°C or more, above the softening point of the silica glass ingot for a period as needed. The viscosity as  $\log \eta$  is 7.6 at the softening point.

Since the ingot is subjected to the high-pressure of 1,000 kgf/cm<sup>2</sup> or more, the density of glass structure will raise, whereby the absolute refractive index,  $n_d$ , (at wave length of 589 nm) increases to more than 1.460 after the process, or in other words more practically, the absolute refractive index of the glass,  $n_d$ , increases in a range from 0.002 to 0.005.

A heating process in an atmosphere containing rare gases and hydrogen mixture is also possible to introduce additional hydrogen in the glass. However, in an atmosphere of temperature more than 1,000°C at pressure more than 1,000 kgf/cm<sup>2</sup>, it is possible to contain hydrogen more than  $1 \times 10^{17}$  molecules/cm<sup>3</sup> hydrogen in the glass without introducing hydrogen into the ambient gas. That is, the temperature is not necessarily to be raised up to the remelting point, but it is sufficient to keep the temperature of about 1,000°C or more in the high-pressure atmosphere.

The sixth feature of the present invention lies in the heating process that is subjected to an ambient atmosphere containing rare gases or main composition thereof.

The heating process provides to fill up vacancies among of ring structures of the silica glass with rare gases, to form hydrogen molecules as well stabilizing the network structure of the glass, whereby the glass is resulted in to show the high durability against high-power laser irradiation.

To achieve effectively the durability against ultraviolet laser irradiation, the glass should contain hydrogen molecules with the concentration of  $1 \times 10^{17}$  molecules/cm<sup>3</sup>, or more. Thus, the synthetic glass should be the silica glass produced from raw material gases including hydrogen element, or produced by oxyhydrogen flame.

The seventh feature of the present invention lies in a step for keeping a pressurized atmosphere at the pressure more than 500 kgf/cm<sup>2</sup> while cooling slowly until below a temperature of about 900°C which is below the strain point of about 1,000°C.

The process is controlled to relieve the internal strain or birefringence at less than 5 nm/cm, whereby a homogeneous silica glass is provided without decreasing the durability against laser irradiation.

Further, more precisely, the high-pressure heating process in the present invention is characterized by cooling process where cooling rate is less than 100°C/h in the temperature range from 1,200 to 900°C, whereby the lowest residual strain can be achieved.

In the case of heating process in the temperature range from 1,000 to 1,600°C, if a lump of glass with striae in three dimensions is used as a starting material, the birefringence will be above 5 nm/cm, with which the optical requirement can not be satisfied. The striae are left remaining even after the high-pressure heating process exerting an adverse effect on optical properties. It is recommended in the present invention that a lump of high-homogeneous silica glass of high-purity striae free at least one direction should be used as a starting material.

The vessel that contains the silica glass for the remelting or heating process is recommended of ones to be of high-temperature resistant refractories or materials. Specifically tungsten, tantalum or platinum-rhodium alloys may be used.

## BRIEF DESCRIPTION OF THE DRAWING

The invention will be described in further detailed with reference to the accompanying drawings in which:

5 Figs. 1(A) and 1(B) are process chart showing a temperature-pressure program in which Fig. 1(A) shows a process for Examples 1 and 2, and Fig. 1(B) shows a process for Example 3,  
Fig. 2 is a front elevation section view showing a HIP apparatus for the production process of the present invention, and  
Fig. 3 is a graph of Raman scattering spectrometry showing the defects in the silica glass.

## DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

The invention will be described in further detail following the practiced Examples.

## A. [Examples 1 and 2.]

Raw material of silicontetrachloride was distilled to remove impurities, and then stored in a vessel of stainless steel with plastics lining of Polytetrafluoroethylene. A plurality of ingots of high-purity silica glass was synthesized from the high-purity raw material of silicontetrachloride by the oxyhydrogen flamehydrolysis, that is, the direct method or the CVD soot remelting method or the soot method.

Concentrations of OH group in the ingots were measured in a range from 600 to 630 mass ppm for the ones by the direct method, and in a range from 180 to 200 mass ppm for the ones by the soot method. Striae were detected in the all ingots.

The striae were observed in accordance with the Japanese Optical Glass Industrial Standards JOGIS 11-1975. The concentration of OH group was measured in accordance with "Optical Determination of OH in Fused Silica" by D.M. Dodd, D.B. Fraser, Journal of Applied Physics, Vol. 37, 1966, p 3911.

The refractive index inhomogeneity,  $\delta n$ , was measured according to the optical interference method applied by the oil-on-plate method with an apparatus, Zygo Mark III System manufactured by Canon Co., Ltd. The light source was a He-Ne laser having a wave length 633 nm.

The ingots were subjected to the heating process above softening point and the slow cooling process, during which the ingots were physically turned over changing the softening direction to eliminate the striae. The treatment was repeated several times. With the repeated processes, the ingots were prepared without stria in three directions with the refractive index inhomogeneity,  $\delta n$ , less than  $2 \times 10^{-6}$ .

The content of the alkali metal elements such as Li, Na, and K, of the alkaline earth elements such as Mg and Ca, and of the transition metal elements such as Ti, Cr, Fe, Ni and Cu were measured, and the ingot showed good results of high-purity. That is, the total content of Li, Na and K was less than 300 mass ppb, the total content of Mg and Ca was less than 200 mass ppb, and the total content of Ti, Cr, Fe, Ni and Cu was less than 500 mass ppb. The concentration of chlorine in ingot was in a range from 50 to 100 mass ppm. The refractive index,  $n_d$ , of the ingots was found to be 1.459.

The content of impurities was measured according to the atomic absorption method. The Cl concentration was measured according to the nephelometric analysis. The refractive index was measured with Abbe's refractometer applying a wave length of 589 nm at the temperature of 23°C.

A plurality of samples was prepared by cutting and grinding the ingots in a form of 100 dia. x 100 mm thick.

From the sample, then, the specimens for the measurement of hydrogen molecules were prepared with mirror finished in three surfaces suitable for the laser Raman scattering spectrometry (Raman method, hereinafter). The procedure of Raman method was subjected in accordance with the paper by V.S. Khotimchenko, et al., in Journal of Applied Spectroscopy, Vol. 46, No. 6, pp 987-991, June, 1987 in which:

the specimens were irradiated by an Ar laser beam (488 nm), then measurements were made for Raman scattering peak of wave number  $4135 \text{ cm}^{-1}$  with basic Raman scattering peak ( $800 \text{ cm}^{-1}$ ). Intensity ratio was calculated as the hydrogen molecule concentration, C, as follow:

$$C = \{[I(4135 \text{ cm}^{-1})]/[I(800 \text{ cm}^{-1})]\} \times k [\text{molecules/cm}^3],$$

where k is a constant,

$$k = 1.22 \times 10^{21}.$$

The results for each specimen after the homogenizing heating/cooling processes showed the hydrogen concentration of less than  $5 \times 10^{16} \text{ molecules/cm}^3$ .

Each sample was put in a platinum-rhodium crucible, and then was subjected to Hot Isostatic Pressing process (HIP process, hereinafter). The process was controlled to remelt in the atmosphere of 100% argon at the pressure of 2,000 kgf/cm<sup>2</sup> and elevated temperature of 1,750°C for 3 hours. Then, according to the temperature-pressure chart as shown in Fig. 1(B), the temperature of ambient atmosphere was cooled slowly to the temperature of 900°C at the rate of 100°C/hr. The pressure was decreased till 1,300 kgf/cm<sup>2</sup> at the rate from 50 to 100 kgf/cm<sup>2</sup>-hr. During a cooling stage of the HIP process, the pressure of 1,300 kg/cm<sup>2</sup> was kept until the temperature of below 200°C. The temperature also had been cooled down slowly below 900°C to the room temperature.

An apparatus adopted in the embodiment of the present invention was a Hot Isostatic Pressing equipment (HIP equipment hereinafter) manufactured by Kobe Steel Co., Ltd. The constitution of the HIP equipment will be described following the illustration shown in Fig. 2. Numeral 11 is a high-pressure cylinder supported with a bottom closure 13, and having a top closure 12 with a gas inlet 12a. The sample was set in a crucible 15 on a support 14 disposed in the cylinder 11. The crucible 15 is surrounded with a heater 16 that is insulated with an insulation mantle 17. No further description will be necessary, as the equipment has been well known.

#### B. [Samples for Examples 3 through 13.]

An ingot was synthesized, of which OH group concentration was 730 mass ppm. The metallic impurities were analyzed to find out to be satisfactory as desired in which: the total content of Li, Na and K was less than 300 mass ppb, the total content of Mg and Ca was less than 200 mass ppb, and the total content of Ti, Cr, Fe, Ni and Cu was less than 500 mass ppb. The chlorine concentration was 50 mass ppm.

A plurality of samples was prepared by cutting and grinding the ingots to form in a size of 100 dia. x 100 mm thick.

Then, each of samples was set in a tungsten crucible to be placed in the HIP equipment. Each of samples was subjected to respective process with the conditions described below.

#### [Example 3.]

In an ambient atmosphere of 100% argon gas at the pressure of 2,000 kgf/cm<sup>2</sup>, the sample was remelted at the temperature of 1,750°C for 3 hours. The temperature was cooled till 1,200°C at the rapid cooling rate of 500°C/hr, then, was cooled till 800°C at the slow cooling rate of 40°C/hr, as shown in the temperature-pressure chart in Fig. 1(B). Corresponding to the cooling process, the pressure was decreased to 1,300 kgf/cm<sup>2</sup> at the rate from 50 to 100 kgf/cm<sup>2</sup>-hr. The pressure of 1,300 kgf/cm<sup>2</sup> was kept until the temperature reached to 500°C. Then, the pressure was reduced slowly to the atmospheric pressure. The temperature also was cooled to the room temperature after slow cooling stage until 800°C.

#### [Example 4 and 5.]

The maximum temperature of the HIP process was set 1,650°C for Example 4, and at 1,400°C for Example 5 respectively. The other conditions, such as cooling rate of temperature and reduction rate of pressure, were the same for Example 3 described above.

#### [Example 6.]

In an atmosphere of 100% argon gas at the pressure of 2,000 kgf/cm<sup>2</sup>, the sample was heat treated at the temperature of 1,000°C for 3 hours. The temperature was cooled till 800°C at the slow cooling rate of about 40°C/hr. Corresponding to the cooling process, the pressure was decreased to above 1,000 kgf/cm<sup>2</sup>. The pressure above 1,000 kgf/cm<sup>2</sup> was kept until the temperature cooled down to 200°C. The atmosphere was kept for a while, and then the pressure was reduced slowly to the atmospheric pressure. The temperature also was cooled down to the room temperature.

#### [Example 7.]

In an atmosphere of 100% argon gas at the pressure of 2,000 kgf/cm<sup>2</sup>, the sample was heated at the temperature of 500°C for 3 hours. Keeping the pressure above 1,000 kgf/cm<sup>2</sup>, the temperature is left to cool down to 200°C. The atmosphere was kept for a while, and then the pressure was reduced slowly to the atmospheric pressure. The temperature was also cooled down to the room temperature.

#### [Example 8.]

In an atmosphere of 100% argon gas at the pressure of 1,000 kgf/cm<sup>2</sup>, the sample was remelted at the temperature of 1,750°C for 3 hours. The temperature was cooled till 1,200°C at the rapid cooling rate of 500°C/hr, then, was cooled



till 800°C at the slow cooling rate of 10°C/hr. Keeping the pressure above 1,000 kgf/cm<sup>2</sup>, the temperature was left to cool down to 500°C. The atmosphere was kept for a while, and then the pressure was reduced slowly to the atmospheric pressure. The temperature was also cooled down to the room temperature, succeeding to the slow cooling process till 800°C.

[Example 9.]

In an atmosphere of 100% argon gas at the pressure of 1 bar without pressurizing, the sample was remelted at the temperature of 1,750°C for 3 hours. The temperature was cooled down to 1,200°C at the rapid cooling rate of 500°C/hr, then, was cooled down to 800°C at the slow cooling rate of 10°C/hr. Then, the temperature was left to cool down to the room temperature.

[Example 10.]

The sample was subjected to the atmosphere of 100% nitrogen gas. The other conditions were the same for the Example 3.

[Example 11.]

The sample was placed in a crucible made of Al<sub>2</sub>O<sub>3</sub>. The other conditions were the same for the Example 3.

[Example 12.]

In an atmosphere of 100% argon gas at the pressure of 2,000 kgf/cm<sup>2</sup>, the sample was remelted at the temperature of 1,750°C for 3 hours. The temperature was cooled till 1,200°C at the rapid cooling rate of 500°C/hr. Then, the pressure was reduced to the atmospheric pressure at the rapid rate of 500 kgf/cm<sup>2</sup>·hr, while the temperature was cooled till 800°C at the slow cooling rate of 40°C/hr. The temperature was left to cool down to the room temperature.

[Example 13.]

In an atmosphere of mixture of 90% argon gas and 10% hydrogen at the pressure of 1,000 kgf/cm<sup>2</sup>, the sample was heat treated at the temperature of 1,000°C for 3 hours. The temperature was then cooled till 800°C at the slow cooling rate of about 10°C/hr. Keeping the pressure above 1,000 kgf/cm<sup>2</sup>, the temperature was left to cool down to 500°C. The atmosphere was kept for a while, and then the pressure was reduced slowly to the atmospheric pressure. The temperature was also left to cool down to the room temperature succeeding to the cooling process till 800°C.

[Examples 14 and 15.]

To confirm the effects of the embodiment of the present invention, a lump of high-purity silica glass without OH group was synthesized by a plasma method from high-purity silicontetrachloride as a raw material. The silica glass was subjected to the stria removing process and the annealing process as was the same to the sample above, then was formed in the size described previously. The sample was subjected to the same process to Example 3. The sample was referred as Example 14.

A lump of powdery natural quartz was remelted by a Verneuil's method to form a sample as well. The sample was subjected to the similar process as to Example 3. The sample was referred as Example 15.

C. [Evaluation of Examples 1 through 15.]

Each of samples for Example 1 through 15 was formed in a plurality of specimens for evaluation in which: two each pieces of specimens for evaluation of durability against excimer laser irradiation in a size 20 x 20 x 10 mm thick with the mirror finishing at both sides, two each pieces of specimens for evaluation of refractive index and Raman scattering method in a size of 5 x 10 x 20 mm with the mirror finishing at three faces, and a lump of powder for measuring dissolved gas contents weighting 1 g.

The measurements of refractive index and concentration of hydrogen molecules were subjected to the methods described previously. The dissolved gases were identified by a gas massspectrometry.

To evaluate the durability against KrF excimer laser irradiation, the irradiation conditions were adjusted to be: the pulse energy of 175 mj/pulse, the energy density of about 400 mj/cm<sup>2</sup> per pulse, the repetition rate of 100 Hz, and the pulse duration of 17 nanoseconds. The irradiation conditions for ArF excimer laser beam were adjusted to be:

the pulse energy of 50 mJ/pulse, the pulse energy density of about 200 mJ/cm<sup>2</sup> per pulse at higher power, the repetition rate of 100 Hz, and the pulse duration of 13 nanoseconds.

The pulse numbers were counted until the internal transmission decrease to 97% at the energy of 5.8 eV (wave length of about 214 nm) in 10 mm thick silica glass specimens. The pulse numbers were deemed as an index of durability against laser irradiation. The internal transmission of the specimens which were exposed to the irradiation at 5.8 eV was more than 99.8%, except those of Examples 11 and 15.

The pulse numbers counted down to the 97% internal transmission enough to practical use would be about  $2 \times 10^6$  that was rated as Fine. A specimen of which pulse numbers further exceeded the number was regarded as Excellent. A specimen that was subordinated to the rating of Fine but seemed to be allowable for practical use was regarded as Fair, which was followed by the rating Failure.

In the Raman method, as shown in Fig. 3, that the two defect peaks at  $D_1$ :495 cm<sup>-1</sup> and  $D_2$ :606 cm<sup>-1</sup> were supposed to correspond to the 4-member ring and 3-member ring with reference to the basic vibration  $W_0$ :800 cm<sup>-1</sup>. The intensity of the spectra of  $D_1$  was measured of the hatched area confined by its own peak and the base border connecting the feet at 470 and 520 cm<sup>-1</sup> thereof. The intensities of  $D_2$  and  $W_0$  were measured respectively of the hatched areas confined by the corresponding peaks and the base borders connecting each foot at 580 and 640 cm<sup>-1</sup>, and at 700 and 950 cm<sup>-1</sup>.

The equations 1 and 2, therefore, shown previously for the intensity ratio could be modified, corresponding to  $I_1$ ,  $I_2$  and  $I_0$ :

$$R1 = D_1 / W_0 \quad \text{Equ. 1'}$$

$$R2 = D_2 / W_0 \quad \text{Equ. 2'}$$

where,

$D_1$ : peak area at 495 cm<sup>-1</sup>,  
 $D_2$ : peak area at 606 cm<sup>-1</sup>, and  
 $W_0$ : peak area at 800 cm<sup>-1</sup>.

Findings of the characteristics and evaluations for the respective samples are given in Table 1.

[Example 1.]

The findings showed excellent characteristics with a raised absolute refractive index increased from 1.459 to 1.461, with a decrease of the scattering intensity of  $D_1$ ,  $D_2$  lines, with a higher concentration of hydrogen molecules included more than  $1 \times 10^{18}$  molecules/cm<sup>3</sup>, and with fairly good findings in every respect to the stria, the homogeneity,  $\delta n$ , and the birefringence. The laser durability was rated as Excellent. Besides the characteristics shown in Table 1, the hydrogen concentration was confirmed for the specimens represented the central part and the surface regions, of which findings showed no significant difference.

[Example 2.]

Findings showed excellent results similar to Example 1, except the rating for the durability against ArF laser irradiation, of which reason could be considered as a poor concentration of OH group as close to 100 ppm.

[Example 3.]

Findings showed excellent results similar to Example 1. It was especially worth to note that the striae were improved from free for one direction to three directions. The durability against laser irradiation was rated as Excellent for both KrF and ArF lasers.

[Example 4.]

Findings showed excellent results similar to Examples 1 through 3 above, except the rating Fine for durability against ArF laser irradiation. It is considered that the low remelting process temperature has reflected to reduce the unstable 3-member ring and 4-member ring not up to expectations.

[Examples 5.]

Findings exhibited fairly good results rated as Fines for durabilities against both lasers irradiations, though the intensity ratios were not reduced further to the Example 4, because the maximum process temperature 1,400°C was below the softening point of about 1,600°C of silica glass.

[Example 6 and 7.]

The remelting process temperature was far below than was Example 5 above, in which the unstable structures of 3-member and 4-member ring were remained considerably, and with a poor content  $1 \times 10^{17}$  molecules/cm<sup>3</sup> of hydrogen molecules. Findings still exhibited Fair rates passable for the practical use for both laser beams.

In Example 7, however, the findings showed the Failure ratings for durability against both laser irradiations due to the lowest temperature of 500°C for the heat treatment process. It is considered, therefore, that the conditions for the Example 6 would be minimum requirements.

[Examples 8 and 9.]

In Example 8 of which pressure for the remelting process was kept as low as 1,000 kgf/cm<sup>2</sup>, findings gave Fine ratings for durability against both laser irradiations. Whereas the finding in Example 9 was rated as Failure for both durabilities, of which sample was subjected under the atmospheric pressure. To achieve the object of the present invention, therefore, it is necessary to subject to the heat treatment in high-pressure, or more practically, at the higher temperature from 500 to 1,000°C or more in the pressurized atmosphere.

[Example 10.]

It was found in the Example 10 that the atmosphere of nitrogen gas, instead of argon gas, resulted in the Failure ratings for the durabilities against both lasers irradiations. It is considered that the nitrogen atmosphere under the high-pressure would produce nitrides in the silica glass. Even in the nitrogen atmosphere, it was considered that the issue could not be prevented, if the process might be subjected to the softening point of about 1,600°C or below.

[Examples 11.]

As shown in Example 11, it was found that the crucible made of Al<sub>2</sub>O<sub>3</sub> was harmful for the durabilities against both lasers irradiations, because alumina could react with silica. It is recommended, therefore, to use either one of crucibles made of Tungsten, Tantalum or platinum-rhodium alloys.

[Examples 12.]

As in the Example 12, the rapid reducing of pressure to the atmospheric pressure that was succeeded by the heating process resulted in the rating Failures. It is required, therefore, that the pressure must be kept as high as 1,000 kgf/cm<sup>2</sup> or more until the temperature decrease to at least 900°C.

[Example 13.]

As in the Example 13 of which atmosphere was consisted of the main composition of argon gas with the additional hydrogen gas, it was found that the glass contained the highest concentration of hydrogen of  $1 \times 10^{19}$  molecules/cm<sup>3</sup>, even though in the poor conditions with the pressure of 1,000 kgf/cm<sup>2</sup> with the temperature of 1,000°C for the HIP process. It showed also good findings resulted in the Excellent ratings for the durabilities against both lasers irradiations.

[Example 14.]

In the Example 14 on the other hand, of which sample was made by the plasma method not to include OH group, it was confirmed that the sample contains the lowest concentration of hydrogen molecules with the ratings Failures for the durabilities against both lasers irradiations, too. It is the prerequisite for the present invention, therefore, that the starting material should be synthesized silica glass made by either the direct method or the soot method including OH group.

[Example 15.]

In the Example 15 of which sample was made from the natural quartz, it was found that the rating for the durabilities against both lasers irradiations resulted in out of question, though the hydrogen concentration had been increased to a fairly good level.

D. [Preparation and Evaluation of Example 16.]

A lump of preform for optical fiber was synthesized by the soot method. The characteristics of the core part of preform were measured. The concentrations were found to be of OH group of 100 mass ppm, of chlorine of 30 mass ppm, and of hydrogen molecule of  $5 \times 10^{16}$  molecules/cm<sup>3</sup>. And the refractive index,  $n_d$ , found to be 1.458. The clad part of the preform was doped with fluorine.

The preform was drawn to form in the size of core in 1 mm dia., with a clad layer in 1.5 mm dia. The fiber was subjected to the HIP process shown in Table 1 to prepare samples for Example 16.

Findings are shown in Table 1 in which the hydrogen molecule concentration has been measured according to the Raman method, and the refractive index has been measured for the powdery sample of the fiber core part by means of the immersion method.

Evaluation was made for the durability against KrF laser irradiation. A piece of fiber with 1 m length was irradiated continuously under the conditions of the initial transmission power of 5 mJ/pulse, and of the transmission power density of 600 mJ/cm<sup>2</sup>/pulse. The pulse numbers were counted with the intention until the initial transmission power reduced to 50%. The findings showed preferable results that the transmission power energy was still remained more than 50% on the irradiation of  $2 \times 10^6$  pulses.

E. [Preparation and Evaluation of Example 17.]

Evaluation for the durability against gamma ray irradiation was made for the sample 3. A lump of silica glass of 10 mm thick was irradiated by the rate of  $10^6$  R/hr for 10 hours. The optical transmission for the light having a wave length of 215 nm was measured which was found to be a preferable amount of 80%.

The foregoing description and examples have been set forth merely to illustrate the invention and are not intended to be limiting. Since modifications of the described embodiments incorporating the substance of the invention may occur to persons skilled in the art, the scope of the invention should be construed to include all variations falling within the ambit of the appended claims thereof.

TABLE 1									
Example No.		1	2	3	4	5	6	7	8
Starting Class	Production Method	Direct Method	Soot Method	Direct Method	Direct Method	Direct Method	Direct Method	Direct Method	Direct Method
	OH Group Conc.: mass ppm	600 to 630	100 to 200	730	730	730	730	730	730
Process Conditions	Striae(s)	Free in 3 Directions	Free in 3 Directions	Free in 1 Direction	Free in 1 Direction	Free in 1 Direction	Free in 1 Direction	Free in 1 Direction	Free in 1 Direction
	Ambient Gas(es)	Ar	Ar	Ar	Ar	Ar	Ar	Ar	Ar
Characteristics of Processed Class	Maximum Temperature: °C	1,750, 3hrs	1,750, 3hrs	1,750, 3hrs	1,550, 3hrs	1,400, 3hrs	1,000, 3hrs	500, 3hrs	1,750, 3hrs
	Temperature Decreasing Rate: °C/h	100 till 900°C, then left to cool	100 till 900°C, then left to cool	500 till 1,200°C, 40 till 800°C, then left to cool	500 till 1,200°C, 40 till 800°C, then left to cool	500 till 1,200°C, 40 till 800°C, then left to cool	40 till 800°C, then left to cool	Left to cool to Room temp.	500 till 1,200°C, 10 till 800°C, then left to cool
	Maximum Pressure: kgf/cm <sup>2</sup>	2,000	2,000	2,000	2,000	2,000	2,000	2,000	1,000
	Pressure Conditions: kgf/cm <sup>2</sup>	Kept 1,300 or more till 200°C, then released	Kept 1,300 or more till 200°C, then released	Kept 1,000 or more till 500°C, then slowly reduced	Kept 1,000 or more till 500°C, then slowly reduced	Kept 1,000 or more till 500°C, then slowly reduced	Kept 1,000 or more till 500°C, then slowly reduced	Kept 1,000 or more till 500°C, then slowly reduced	Kept 1,000 or more till 500°C, then left to release
	Crucible Material	Pt-Rh Alloys	Pt-Rh Alloys	Tungsten	Tungsten	Tungsten	Tungsten	Tungsten	Tungsten
	Absolute Refractive Index: nd	1.461	1.462	1.461	1.461	1.461	1.461	1.458	1.461
	Dissolved Gas(es)	Ar, H <sub>2</sub>	Ar, H <sub>2</sub>	Ar, H <sub>2</sub>	Ar, H <sub>2</sub>	Ar, H <sub>2</sub>	Ar, H <sub>2</sub>	Ar, O <sub>2</sub> , H <sub>2</sub>	Ar, H <sub>2</sub>
	Hydrogen Conc.: molecules/cm <sup>3</sup>	3×10 <sup>16</sup> to 4×10 <sup>16</sup>	3×10 <sup>16</sup> to 3.5×10 <sup>16</sup>	3×10 <sup>16</sup>	3×10 <sup>16</sup>	1×10 <sup>16</sup>	1×10 <sup>16</sup>	< 5×10 <sup>16</sup>	1×10 <sup>16</sup>
	R <sub>1</sub> Ratio	0.405	0.405	0.42	0.45	0.45	0.53	0.54	0.43
	R <sub>2</sub> Ratio	0.110	0.110	0.10	0.13	0.13	0.17	0.17	0.12
	Striae(s)	Free in 3 Directions	Free in 3 Directions	Free in 3 Directions	Free in 1 Direction	Free in 1 Direction	Free in 1 Direction	Free in 1 Direction	Free in 3 Directions
	Maximum Refractive Index Fluctuation: δn	< 2×10 <sup>-6</sup>	< 2×10 <sup>-6</sup>	2×10 <sup>-6</sup>	2×10 <sup>-6</sup>	3×10 <sup>-6</sup>	2×10 <sup>-6</sup>	5×10 <sup>-6</sup>	2×10 <sup>-6</sup>
	Birefringence: nm/cm	< 5	< 5	< 5	5	5	5	< 5	5
	Pulse Numbers till the Internal Transmission decrease to 97% at the Energy of 5.8 eV	> 2×10 <sup>6</sup>	> 2×10 <sup>6</sup>	> 2×10 <sup>6</sup>	> 2×10 <sup>6</sup>	2×10 <sup>6</sup>	6×10 <sup>6</sup>	< 1×10 <sup>6</sup>	2×10 <sup>6</sup>
	Durability against KrF Irradiation	Excellent	Excellent	Excellent	Excellent	Fine	Fair	Failure	Fine
	Pulse Numbers till the Internal Transmission decrease to 97% at the Energy of 5.8 eV	> 2×10 <sup>6</sup>	2×10 <sup>6</sup>	> 2×10 <sup>6</sup>	2×10 <sup>6</sup>	1×10 <sup>6</sup>	2×10 <sup>6</sup>	< 1×10 <sup>6</sup>	8×10 <sup>6</sup>
	Durability against ArF Irradiation	Excellent	Fine	Excellent	Fine	Fine	Fair	Failure	Fine
	2θ								

Ratings: Excellent &gt; Fine &gt; Fair &gt; Failure

TABLE 1 (cont.)																
Example No.	Production Method	9	10	11	12	13	14	15	16							
										Direct Method	Direct Method	Direct Method	Plasma Method	Verneuil's Method	Soot Method	
Starting Class	OH Group Conc.: mass ppm	730	730	730	730	730	< 1	210	100							
	Striae(e)	Free in 1 Direction	Free in 1 Direction	Free in 1 Direction	Free in 1 Direction	Free in 1 Direction	Free in 1 Direction	Striae in 3 Directions	—							
	Ambient Gas(es)	Ar	N <sub>2</sub>	Ar	Ar	H <sub>2</sub> 10% / Ar 90%	Ar	Ar	H <sub>2</sub> 5% / Ar 95%							
	Maximum Temperature: °C	1,750, 3hrs	1,750, 3hrs	1,750, 3hrs	1,750, 3hrs	1,000, 3hrs	1,750, 3hrs	1,750, 3hrs	1,000, 1hr							
Process Conditions	Temperature Decreasing Rate: °C/h	500 till 1,200°C, 10 till 800°C, then left to cool	500 till 1,200°C, 40 till 800°C, then left to cool	500 till 1,200°C, 40 till 800°C, then left to cool	500 till 1,200°C, 40 till 800°C, then left to cool	10 till 800°C, then left to cool	500 till 1,200°C, 40 till 800°C, then left to cool	500 till 1,200°C, 40 till 800°C, then left to cool	100 till 800°C, then left to cool							
	Maximum Pressure: kgf/cm <sup>2</sup>	1 abs.	2,000	2,000	2,000	1,000	2,000	2,000	1,000							
	Pressure Conditions: kgf/cm <sup>2</sup>	—	Kept 1,300 or more till 500°C, then left to release	Kept 1,300 or more till 500°C, then left to release	Released at the rapid rate of 500 kgf/cm <sup>2</sup> /hr to room temp.	Kept 1,000 till 500°C, then left to release	Kept 1,000 or more till 500°C, then slowly reduced	Kept 1,300 or more till 500°C, then left to release	Kept 1,000 or more till 500°C, then slowly reduced							
	Crucible Material	Tungsten	Tungsten	Alumina	Tungsten	Tungsten	Tungsten	Tungsten	Tungsten	Silicon Carbide						
Characteristics of Processed Glass	Absolute Refractive Index: n <sub>d</sub>	1.458	1.461	1.461	1.458	1.461	1.461	1.461	1.460 to 1.465							
	Dissolved Gas (cs)	O <sub>2</sub> , H <sub>2</sub> O, H <sub>2</sub>	N <sub>2</sub> , H <sub>2</sub>	Ar, H <sub>2</sub>	Ar, H <sub>2</sub>	H <sub>2</sub>	Ar	Ar, H <sub>2</sub>	H <sub>2</sub>							
	Hydrogen Conc.: molecules/cm <sup>3</sup>	< 5×10 <sup>16</sup>	3×10 <sup>16</sup>	3×10 <sup>16</sup>	8×10 <sup>16</sup>	5×10 <sup>16</sup>	< 5×10 <sup>16</sup>	4×10 <sup>17</sup>	1×10 <sup>18</sup>							
	R <sub>1</sub> Ratio R <sub>2</sub> Ratio	0.55 0.17	0.45 0.15	0.43 0.12	0.45 0.15	0.50 0.14	—	?	—							
	Striae(e)	Free in 1 Direction	Free in 3 Directions	Free in 3 Directions	Free in 1 Direction	Free in 1 Direction	Free in 3 Directions	Striae in 3 Directions	—							
	Maximum Refractive Index Fluctuation: δn	5×10 <sup>-4</sup>	2×10 <sup>-4</sup>	2×10 <sup>-4</sup>	2×10 <sup>-4</sup>	1×10 <sup>-4</sup>	1×10 <sup>-4</sup>	1×10 <sup>-4</sup>	—							
	Birefringence: n <sub>d</sub> /cm	< 6	10	< 5	5	5	5	5	—							
	Pulse Numbers till the Internal Transmission decrease to 97% at the Energy of 5.8 eV	< 1×10 <sup>6</sup>	< 1×10 <sup>6</sup>	1×10 <sup>6</sup>	< 1×10 <sup>6</sup>	> 1×10 <sup>6</sup>	< 1×10 <sup>6</sup>	Out of Question	Upon Irradiation of 2×10 <sup>6</sup> pulses, showed the Internal Transmission of 50% or more.							
	Durability against KrF Irradiation	Failure	Failure	Fine	Failure	Excellent	Failure	Failure	Excellent							
	Pulse Numbers till the Internal Transmission decrease to 97% at the Energy of 5.8 eV	< 1×10 <sup>6</sup>	< 1×10 <sup>6</sup>	Out of Question	< 1×10 <sup>6</sup>	> 1×10 <sup>6</sup>	< 1×10 <sup>6</sup>	Out of Question	—							
	Durability against ArF Irradiation	Failure	Failure	Failure	Failure	Excellent	Failure	Failure	—							

## Claims

1. An optical member made of high-purity transparent synthetic silica glass, the optical member comprising:  
having absolute refractive index,  $n_d$ , at a wavelength of 589 nm of 1.460 or more, having hydrogen molecule concentration of about  $1 \times 10^{17}$  molecules/cm<sup>3</sup> or more, and a OH group concentration of at least 180 mass ppm.
2. An optical member as claimed in claim 1, wherein the optical member is made from a lump of high-purity transparent synthetic silica glass as a starting material, in which the silica glass is synthesized by the oxyhydrogen flame hydrolysis method.
3. An optical member as claimed in claim 1, wherein the optical member contains rare gas elements together with hydrogen molecules.
4. An optical member as claimed in claim 1, wherein each of intensity ratios  $R_1$  and  $R_2$  of the optical member is respectively smaller than 0.48 and 0.15 in which the intensity ratio  $R_1$  is a ratio of scattering peak intensity  $I_1$  at wave numbers of 495 cm<sup>-1</sup> to scattering peak intensity  $I_0$  at wave numbers of 800 cm<sup>-1</sup> for the basic vibration between silicon and oxygen measured by the laser Raman scattering spectrometry, and in which the scattering ratio  $R_2$  is a ratio of scattering intensity  $I_2$  at wave numbers of 606 cm<sup>-1</sup> to the scattering intensity  $I_0$  for the basic vibration.
5. An optical member as claimed in claim 1, wherein the maximum refractive index fluctuation,  $\delta n$ , of the optical member along the incident of light is less than  $5 \times 10^{-6}$ , or more preferably is less than  $2 \times 10^{-6}$ .
6. An optical member as claimed in claim 1, wherein the concentration of chlorine in the optical member is less than 500 mass ppm, or more preferably is less than 200 mass ppm.
7. An optical member as claimed in claim 1, wherein the optical member is free from striae at least in one direction.
8. An optical member as claimed in claim 1, wherein the birefringence of the optical member is less than 10 nm/cm, or more preferably is less than 5 nm/cm.
9. An optical member as claimed in claim 1, wherein the impurity content in the optical member is such that the total amount of Li, Na and K is 300 mass ppb or less, the total amount of Mg, and Ca is 200 mass ppb or less, the total amount of Ti, Cr, Fe, Ni and Cu is 500 mass ppb or less.
10. An optical member as claimed in claim 1, wherein the high-power light source is either one of a YAG laser (1064 nm), a He-Ne laser (633 nm), an Ar laser (from 350 to 515 nm), a KrF laser (248 nm) or an ArF excimer laser.
11. An optical member as claimed in claim 1, wherein the optical member is either one of a lens, a prism, a filter, a window, a mirror, a light transmission member or a semifinished product thereof used in optical apparatus that uses an excimer laser, a YAG harmonics laser, or other high-power ultraviolet lasers.
12. An optical member as claimed in claim 1, wherein the optical member is either one of a lens, a prism, a filter, a window, a mirror, a light transmission member or a semifinished product thereof placed in an environment where it is exposed to gamma rays, X-rays, cosmic rays or other radiation.
13. An optical member as claimed in claim 1, wherein the materials stoichiometry is set to  $\text{SiO}_{2+x}$  with x in the range of +0.0001 to -0.001.
14. A laser optical apparatus comprising an optical member made of a transparent synthetic silica glass member having a refractive index,  $n_d$ , of 1.460 or more, containing hydrogen molecules in an amount at least about  $1 \times 10^{17}$  molecules/cm<sup>3</sup> and a OH group concentration of at least 180 mass ppm, wherein the optical member is intended to be irradiated with a light source either one of a YAG laser (1,064 nm), a He-Ne laser (633 nm), an Ar laser (from 350 to 515 nm), a KrF laser (248 nm), an ArF excimer laser (193 nm) or an excimer laser which irradiates a high-power laser beam having an energy density more than about 10 mJ/cm<sup>2</sup> per pulse.
15. A method of producing an optical member, the method comprising the steps of:  
using a lump of high-purity transparent synthetic silica glass as a starting material, heating the silica glass at a temperature possible to remelt the silica glass in a high-pressure atmosphere of rare gas of at least 1000 kgf/cm<sup>2</sup>, keeping the atmosphere for a desirable period to contain hydrogen until the concentration of molecules in the silica

glass is above  $1 \times 10^{17}$  molecules/cm<sup>3</sup>,  
cooling slowly at least to a temperature of 900° C under the high-pressure atmosphere of at least 500 kgf/cm<sup>2</sup>,  
wherein the cooling rate in a range of temperatures from 1,200 to 900° C is 100° C/hr or less  
whereby the generation of strains in the glass is suppressed, and hydrogen molecules are included in the glass.

- 5 16. The method of claim 15, wherein the step of cooling comprises cooling further at least to a temperature of 500 ° C under a high-pressure atmosphere, of at least 500 kgf/cm<sup>2</sup>.
17. The method of claim 15, wherein the lump of synthetic silica glass is a silica glass material synthesized by the oxyhydrogen flame hydrolysis.
18. The method of claim 15, wherein the temperature possible to remelt the silica glass in the heating step is higher than 1,600° C.
- 15 19. The method of claim 15, wherein the temperature possible to melt the silica glass in the heating step is higher than the softening point whose viscosity as log  $\eta$  is 7.6.
20. The method of claim 15, wherein a high-homogeneous silica glass material of high-purity, and being free from striae in at least one direction is used for the lump of transparent synthetic silica glass as the starting material.
21. The method of claim 15, wherein the material of vessel to place the silica glass for remelting is either one of tungsten, tantalum, platinum-rhodium alloys or refractories.

#### Patentansprüche

- 25 1. Optisches Bauteil aus hochreinem, transparenten, synthetischen Quarzglas mit: einem absoluten Brechungsindex  $n_d$  bei einer Wellenlänge von 589 nm von 1460 oder mehr, einer Wasserstoffmolekül-Konzentration von etwa  $1 \times 10^{17}$  Molekülen/cm<sup>3</sup> oder mehr und einer Hydroxylgruppen-Konzentration von mindestens 180 Gew.-ppm.
- 30 2. Optisches Bauteil nach Anspruch 1, dadurch gekennzeichnet, daß es aus einem Posten hochreinen, transparenten, synthetischen Quarzglases als Ausgangsmaterial hergestellt wird, wobei das Quarzglas mit dem Knallgasflamme-Hydrolyseverfahren synthetisiert wird.
- 35 3. Optisches Bauteil nach Anspruch 1, dadurch gekennzeichnet, daß es Edelgaselemente zusammen mit Wasserstoffmolekülen enthält.
- 40 4. Optisches Bauteil nach Anspruch 1, dadurch gekennzeichnet, daß der Quotient der Intensitäten  $R_1$  und  $R_2$  des optischen Bauteils kleiner ist als 0,48 bzw. 0,15, wobei der Intensitätsquotient  $R_1$  der Quotient aus der Streuungs-Spitzenintensität  $I_1$  bei Wellenzahlen von 495 cm<sup>-1</sup> und der Streuungs-Spitzenintensität  $I_0$  bei Wellenzahlen von 800 cm<sup>-1</sup> für die Grundschiwingung zwischen Silizium und Sauerstoff, gemessen mit der Laser-Raman-Spektrometrie, ist, und der Streuungsquotient  $R_2$  der Quotient aus der Streuungsintensität  $I_2$  bei Wellenzahlen von 606 cm<sup>-1</sup> und der Streuungsintensität  $I_0$  für die Grundschiwingung ist.
- 45 5. Optisches Bauteil nach Anspruch 1, dadurch gekennzeichnet, daß die maximale Schwankung des Brechungsindex  $\delta n$  des optischen Bauteils längs des eingestrahnten Lichts kleiner ist als  $5 \times 10^{-6}$ , vorzugsweise jedoch kleiner als  $2 \times 10^{-6}$ .
- 50 6. Optisches Bauteil nach Anspruch 1, dadurch gekennzeichnet, daß die Chlorkonzentration in dem optischen Bauteil kleiner ist als 500 Gew.-ppm, vorzugsweise jedoch kleiner als 200 Gew.-ppm.
7. Optisches Bauteil nach Anspruch 1, dadurch gekennzeichnet, daß es mindestens in einer Richtung schlierenfrei ist.
8. Optisches Bauteil nach Anspruch 1, dadurch gekennzeichnet, daß die Doppelbrechung des optischen Bauteils kleiner ist als 10 nm/cm, vorzugsweise jedoch kleiner als 5 nm/cm.
- 55 9. Optisches Bauteil nach Anspruch 1, dadurch gekennzeichnet, daß sein Gehalt an Verunreinigungen derart ist, daß der Gesamtgehalt an Li, Na und K 300 Gew.-ppb oder weniger beträgt, der Gesamtgehalt an Mg und Ca 200 Gew.-ppb oder weniger beträgt und der Gesamtgehalt an Ti, Cr, Fe, Ni und Cu 500 Gew.-ppb oder weniger beträgt.



10. Optisches Bauteil nach Anspruch 1, dadurch gekennzeichnet, daß die Hochleistungsstrahlenquelle entweder ein YAG-Laser (1064 nm), ein He-Ne-Laser (633 nm), ein Ar-Laser (von 350 bis 515 nm), ein KrF-Laser (248 nm) oder ein ArF-Excimer-Laser ist.
- 5 11. Optisches Bauteil nach Anspruch 1, dadurch gekennzeichnet, daß es entweder eine Linse, ein Prisma, ein Filter, ein Fenster, ein Spiegel, ein lichtdurchlässiges Bauteil oder ein Halbfabrikat davon ist, zur Verwendung in einer optischen Vorrichtung, die einen Excimer-Laser, einen YAG-Laser oder andere UV-Hochleistungs-Laser aufweist.
12. Optisches Bauteil nach Anspruch 1, dadurch gekennzeichnet, daß es entweder eine Linse, ein Prisma, ein Filter,  
10 ein Fenster, ein Spiegel, ein lichtdurchlässiges Bauteil oder ein Halbfabrikat davon ist, das in eine Umgebung gebracht wird, in der es Gammastrahlen, Röntgenstrahlen, kosmischen Ultrastrahlen oder anderer Strahlung ausgesetzt ist.
13. Optisches Bauteil nach Anspruch 1, dadurch gekennzeichnet, daß die Materialstöchiometrie auf  $\text{SiO}_{2+x}$  mit x im Bereich zwischen +0,0001 und -0,001, festgesetzt ist.
- 15 14. Optische Laservorrichtung, die ein optisches Bauteil aus transparentem, synthetischen Quarzglas mit einem Brechungsindex  $n_d$  von 1460 oder mehr umfaßt, und das einen Wasserstoffmolekül-Gehalt von mindestens etwa  $1 \times 10^{17}$  Molekülen/cm<sup>3</sup> und eine Hydroxylgruppen-Konzentration von mindestens 180 Gew.-ppm aufweist, dadurch gekennzeichnet, daß das optische Bauteil dazu dient mit einer Strahlungsquelle, entweder einem YAG-Laser (1064  
20 nm), einem He-Ne-Laser (633 nm), einem Ar-Laser (von 350 bis 515 nm), einem KrF-Laser (248 nm), einem ArF-Excimer-Laser (193 nm) oder einem Excimer-Laser, der einen Hochleistungslaserstrahl mit einer Energiedichte von mehr als etwa 10 mJ/cm<sup>2</sup> pro Pulsaussendet, bestrahlt zu werden.
15. Verfahren zur Herstellung eines optischen Bauteils, das folgende Verfahrensschritte umfaßt:  
25 Verwendung eines Postens hochreinen, transparenten, synthetischen Quarzglases als Ausgangsmaterial, Erhitzen des Quarzglases auf eine Temperatur, die das Schmelzen des Quarzglases in einer Hochdruck-Edelgas-Atmosphäre von mindestens 1000 kgf/cm<sup>2</sup> ermöglicht, Erhaltung eines Wasserstoffgehalts während eines vorgegebenen Zeitraumes in der Atmosphäre, bis die Molekülkonzentration im Quarzglas mehr als  $1 \times 10^{17}$  Moleküle/cm<sup>3</sup> beträgt,  
30 langsames Abkühlen auf eine Temperatur von mindestens 900° C unter einer Hochdruck-Atmosphäre von mindestens 500 kgf/cm<sup>2</sup>, dadurch gekennzeichnet, daß die Abkühlrate im Temperaturbereich von 1200 bis 900° C 100° C/hr oder weniger beträgt, wobei die Entstehung von Spannungen in dem Glas unterdrückt wird und Wasserstoffmoleküle im Glas eingeschlossen werden.
- 35 16. Verfahren nach Anspruch 15, dadurch gekennzeichnet, daß der Verfahrensschritt des Abkühlens ein weiteres Abkühlen auf eine Temperatur von mindestens 500° C unter einer Hochdruck-Atmosphäre von mindestens 500 kgf/cm<sup>2</sup> umfaßt.
- 40 17. Verfahren nach Anspruch 15, dadurch gekennzeichnet, daß der Posten synthetischen Quarzglases ein Quarzglasmaterial ist, das mit der Knallgasflamme-Hydrolyse synthetisiert wurde.
18. Verfahren nach Anspruch 15, dadurch gekennzeichnet, daß die Temperatur zum Schmelzen des Quarzglases beim Verfahrensschritt des Erhitzens höher ist als 1600° C.
- 45 19. Verfahren nach Anspruch 15, dadurch gekennzeichnet, daß die Temperatur zum Schmelzen des Quarzglases beim Verfahrensschritt des Erhitzens höher ist als der Erweichungspunkt, dessen Viskosität ausgedrückt  $\log \eta$ , 7,6 beträgt.
- 50 20. Verfahren nach Anspruch 15, dadurch gekennzeichnet, daß ein sehr homogenes Quarzglasmaterial hoher Reinheit, das mindestens in einer Richtung schlierenfrei ist, als Ausgangsmaterial für den Klumpen transparenten, synthetischen Quarzglases verwendet wird.
21. Verfahren nach Anspruch 15, dadurch gekennzeichnet, daß das Material des Gefäßes, in dem sich das Quarzglas zum Schmelzen befindet, entweder aus Wolfram, Tantal, Platinrhodium-Legierungen oder feuerfesten Stoffen  
55 besteht.

## Revendications

1. Elément optique formé d'un verre de silice de synthèse transparent et très pur, l'élément optique ayant un indice de réfraction absolu  $n_d$  à une longueur d'onde de 589 nm qui est supérieur ou égal à 1,460, une concentration de molécules d'hydrogène d'environ  $1.10^{17}$  molécules par centimètre cube ou plus, et une concentration massique de groupe OH au moins égale à 180 ppm.
2. Elément optique selon la revendication 1, dans lequel l'élément optique est formé à partir d'une masse d'un verre de silice de synthèse transparent et très pur comme matière première, le verre de silice étant synthétisé par un procédé d'hydrolyse à la flamme oxyhydrique.
3. Elément optique selon la revendication 1, dans lequel l'élément optique contient des éléments des gaz rares avec des molécules d'hydrogène.
4. Elément optique selon la revendication 1, dans lequel chacun des rapports d'intensités  $R_1$  et  $R_2$  de l'élément optique est rendu inférieur à 0,48 et 0,15 respectivement, le rapport d'intensité  $R_1$  étant le rapport de l'intensité  $I_1$  du pic de diffusion au nombre d'onde de  $495\text{ cm}^{-1}$  à l'intensité  $I_0$  du pic de diffusion au nombre d'onde de  $800\text{ cm}^{-1}$  pour la vibration fondamentale entre le silicium et l'oxygène, mesuré par spectrométrie de diffusion Raman laser, le rapport de diffusion  $R_2$  étant le rapport de l'intensité de diffusion  $I_2$  au nombre d'onde de  $606\text{ cm}^{-1}$  à l'intensité de diffusion  $I_0$  pour la vibration fondamentale.
5. Elément optique selon la revendication 1, dans lequel la fluctuation maximale d'indice de réfraction  $\delta n$  de l'élément optique suivant le trajet de lumière incidente est inférieure à  $5.10^{-6}$  ou de préférence à  $2.10^{-6}$ .
6. Elément optique selon la revendication 1, dans lequel la concentration massique du chlore dans l'élément optique est inférieure à 500 ppm et de préférence à 200 ppm.
7. Elément optique selon la revendication 1, dans lequel l'élément optique est dépourvu de stries au moins dans une direction.
8. Elément optique selon la revendication 1, dans lequel la biréfringence de l'élément optique est inférieure à 10 nm/cm et de préférence à 5 nm/cm.
9. Elément optique selon la revendication 1, dans lequel la teneur massique en impuretés de l'élément optique est telle que la quantité massique totale de Li, Na et K est inférieure ou égale à 300 ppb, la quantité massique totale de Mg et Ca est inférieure ou égale à 200 ppb, et la quantité massique totale de Ti, Cr, Fe, Ni et Cu est inférieure ou égale à 500 ppb.
10. Elément optique selon la revendication 1, dans lequel la source lumineuse de grande puissance est soit un laser YAG (1 064 nm), soit un laser He-Ne (633 nm), soit un laser à Ar (350 à 515 nm), soit un laser à KrF (248 nm), soit un laser à excimère de ArF.
11. Elément optique selon la revendication 1, dans lequel l'élément optique est une lentille, un prisme, un filtre, une fenêtre, un miroir, un organe transmettant la lumière ou un produit semi-fini utilisé dans un appareil optique qui met en oeuvre un laser à excimère, un laser à harmoniques de YAG ou d'autres lasers à ultraviolet de grande puissance.
12. Elément optique selon la revendication 1, dans lequel l'élément optique est une lentille, un prisme, un filtre, une fenêtre, un miroir, un élément transmettant la lumière ou un produit semi-fini placé dans des conditions dans lesquelles il est exposé à des rayons gamma, X ou cosmiques ou à un autre rayonnement.
13. Elément optique selon la revendication 1, dans lequel la stoechiométrie des matières correspond à  $\text{SiO}_{2+x}$ , X étant compris entre +0,0001 et -0,001.
14. Appareil optique à laser comprenant un élément optique formé d'un élément de verre de silice de synthèse qui est transparent et a un indice de réfraction  $n_d$  supérieur ou égal à 1,460, contenant des molécules d'oxygène en quantité au moins égale à environ  $1.10^{17}$  molécules par centimètre cube et une concentration massique de groupe OH au moins égale à 180 ppm, l'élément optique étant destiné à être irradié par une source lumineuse qui est choisie parmi un laser à YAG (1 064 nm), un laser He-Ne (633 nm), un laser à Ar (350 à 515 nm), un laser à KrF (248 nm),

un laser à excimère de ArF (193 nm) ou un laser à excimère qui projette un faisceau laser de grande puissance ayant une densité d'énergie supérieure à 10 mJ/cm<sup>2</sup> par impulsion.

15. Procédé de production d'un organe optique, le procédé comprenant les étapes suivantes :
  - 5 l'utilisation d'une masse d'un verre de silice de synthèse transparent de grande pureté comme matière première,  
le chauffage du verre de silice à une température permettant la refusion du verre de silice en atmosphère à haute pression de gaz rares d'au moins 1 000 bar (1 000 kgf/cm<sup>2</sup>),  
le maintien de l'atmosphère pendant une période souhaitable afin que le verre de silice contienne de l'hydrogène à une concentration de molécules supérieure à 1.10<sup>17</sup> molécules par centimètre cube, et  
10 le refroidissement lent au moins à une température de 900 °C en atmosphère à haute pression d'au moins 500 bar (500 kg/cm<sup>2</sup>), la vitesse de refroidissement dans une plage de température comprise entre 1 200 et 900 °C étant de 100 °C/h ou moins,  
si bien que la création de déformations de verre est supprimée et les molécules d'hydrogène sont incorporées  
15 au verre.
  16. Procédé selon la revendication 15, dans lequel l'étape de refroidissement comprend un refroidissement supplémentaire au moins à une température de 500 °C en atmosphère à haute pression d'au moins 500 bar (500 kgf/cm<sup>2</sup>).
  - 20 17. Procédé selon la revendication 15, dans lequel la masse de verre de silice de synthèse est une matière de verre de silice synthétisée par hydrolyse à la flamme oxyhydrique.
  18. Procédé selon la revendication 15, dans lequel la température qui peut être utilisée pour la refusion du verre de silice dans l'étape de chauffage dépasse 1 600 °C.
  - 25 19. Procédé selon la revendication 15, dans lequel la température qui peut être utilisée pour la fusion du verre de silice dans l'étape de chauffage est supérieure à la température de ramollissement dont la viscosité sous forme du logarithme log $\eta$  est de 7,6.
  - 30 20. Procédé selon la revendication 15, dans lequel une matière très homogène de verre de silice de grande pureté, dépourvue de stries dans une direction au moins, est utilisée comme masse de verre de silice de synthèse transparent comme matière première.
  - 35 21. Procédé selon la revendication 15, dans lequel la matière du récipient dans lequel est placé le verre de silice lors de la refusion est formé de tungstène, de tantale, d'alliage de platine et de rhodium ou d'un réfractaire.

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FIG. 1A

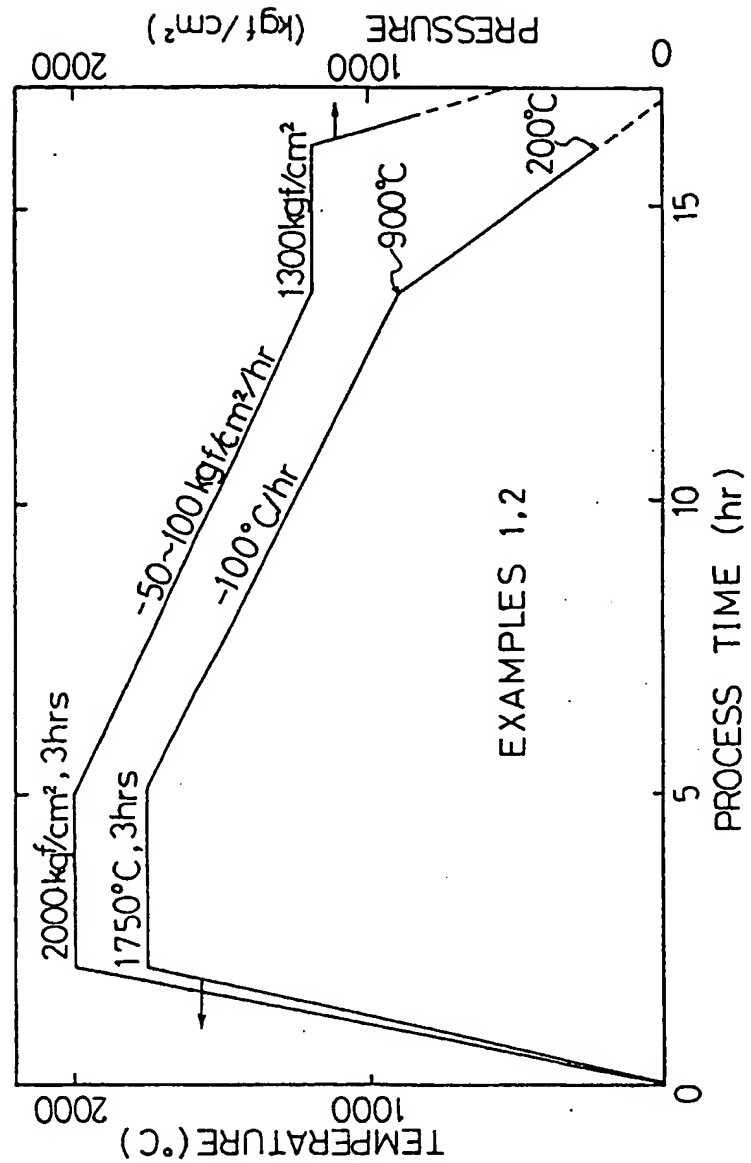


FIG. 1B

